Multiple Drop Interactions with Substrates

G. Desie[1], A. Monteux[1], D. Vadillo[2], and A. Soucemarianadin[2]
[1]Agfa-Gevaert N.V., Mortsel, Belgium
[2]LEGI, UMR 5519, University Joseph Fourier, Grenoble, France

Abstract

The impact of liquid drops with a solid surface has been studied as basic research on jet impingement and for applications in ink-jet printing. However, accurate information is still missing about the physics of the relevant phenomena for the case where multiple droplets impinge successively onto a solid, which is a quite frequent phenomenon in ink-jet printing.

The present study considers the impact of single and two successive drops onto a solid surface with special emphasis on the following situation: the leading drop impinges onto the dry solid surface and comes to rest after eventual oscillations with a given contact angle depending on the interactions between the fluid and the substrate; the incoming drop then impacts onto the top of the previous droplet in an axisymmetric manner. The preliminary experiments performed at low velocities show that after coalescence of the two drops, the swelling behavior and oscillations of the liquid mass is very much alike to the case of a single drop of larger size.

The experimental methods used to study the relevant phenomena are based on high speed cinematography and phase controlled ultra short snap shots of the impact process. A range of flow regimes is covered with the occurrence of spreading, retraction and oscillation of the liquid mass. The above mentioned devices allow to observe in detail the large deformations experienced by the drops over very small time scales, the encapsulation of the incoming drop by the static one, the propagation of instabilities on the liquid mass and the eventual recoiling of the drops.

Finally, the different results that have been obtained are compared with existing data, the possible physical mechanisms are pinpointed and explained and a unified framework of the impact process taking into account the image quality on substrates during actual ink-jet printing is suggested.

Introduction

A large number of engineering applications are concerned with drop impact. Some of these include nuclear reactor cooling where heat transfer is affected by the drop dynamics upon impact of the drop with a solid surface, or the deleterious effect of high velocity rain drops on solid structures and on soils. Detailed knowledge of droplet impingement on solid materials is also critical for overall process development and advancement of engineering operations such as spray cooling and/or spray coating.

The fluid flow associated with impinging drops is rather complicated because of the extreme deformation of the droplet surface occurring within very short time scales. In the case of low impact velocities, the spreading regime is essentially controlled by the surface tension through appropriate dimensionless numbers.[1] When impact velocities become important, it has been shown that compressibility effects play a major role.[2] More recently Mundo *et al.*[3] have reviewed in detail the droplet wall collision problem from an experimental point of view.

The work, which is presented here, is connected to ink-jet printing where drop impact onto solid surfaces is a ubiquitous phenomenon. The emphasis is on the characterization of phenomena related to low speed impacts of single and multiple drops onto a variety of solid surfaces. Through these experiments not only the effects of dynamic impact conditions but also the wetting effects by detailing drop velocity, shape and size at various steps of the spreading phase[4] are investigated. The impact of single drops are simulated numerically using models based on the variational principle[1,5] and the work which still needs to be done for improving the agreement with experimental results is indicated.

In the last section, this study considers the fate of an incoming droplet impinging on an other droplet which is resting under steady state conditions on top of the substrate. This situation happens quite often in ink-jet printing where a variety of drop-onto-drop impacts (direct hit, partial hit, miss-hit) can be observed.[6] An axisymmetric landing (direct hit) of the second drop onto the first one[7] is considered here since this case is simpler than the other situations. The transient interaction phenomena between the two drops are then examined in detail and comparisons with the case of a single drop are given. Emphasis is given on the oscillation of the liquid mass constituted of two drops and the experimental results are compared with theoretical predictions.

As specified earlier, in order not to obscure the different aspects, it was chosen here to study the impact of a single drop and then to consider the case of axisymmetric landing. This is done by using a proprietary pseudo-cinematography method[8] where the evolution of the drop dynamics is reconstructed with photographs of different droplets taken at successive stages of the impact process. The main assumption is that the impact process is fully deterministic.

The particular impacts that are presented here are for relevant dimensionless numbers of interest in ink-jet printing.[1,4] The selected results may be characterized as the interplay between inertial effects, which are shown to dominate the early spreading of the fluid and the viscous, and surface tension forces, which arrest the spreading and eventually bring the fluid to an equilibrium configuration.

Experimental

The experimental setup (figure 1) used in this work has several droplet generating devices in order to cover the full range of droplet sizes. A syringe pump for forming large drops (several millimeters) is used whilst commercially available printheads are utilized for generating small drops in the range of tens of micrometers. The set-up also includes an illumination source, a camera and an optical system coupled to an image recording system. Special triggering electronics combined with appropriate software allow to perform the pseudo-cinematography process.

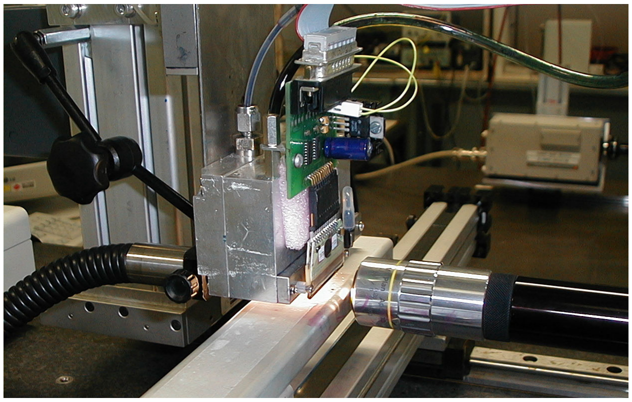

Figure 1. Experimental set-up with Xe-light, IJT printhead, and a camera with fast shutter

Materials

The fluids that were used in this study were distilled water and commercially available aqueous inks especially tuned for piezoelectric print-heads (AgfaJet Sherpa Cyan Dye ink) as well as other ink compositions. The latter fluids basically contained AgfaJet Sherpa Dye ink compositions and glycerol in order to change the viscosity and surface tension. The range of viscosities covered ranges from 1 mPa.s to 260 mPa.s and that of static surface tension of fluids was varied between 33 and 40 mN/m. These characteristics were respectively measured using a Brookfield DVII viscometer and a Krüss K9 digital tensiometer.

Substrate materials with different wetting properties were used throughout this work. The two used for water impacts had the following composition: The hydrophobic one with almost a 80 degrees contact angle is a non-absorbing substrate of polyester with a true polyesterterephtalate surface: with no pores and of course no absorption. The more hydrophilic one with a 35 degrees contact angle is a non-absorbing PET substrate with a top adhesive layer with a composition based on vinylidene chloride copolymer and colloidal silica (80/20). This layer is non porous and has a thickness of about 200 nm. In fact this layer has a small absorptive power but only for a very limited amount of ink. Compared to the microporous and polymeric blend materials that are used elsewhere[1,9] (typical coating thickness of 20 to 40 μm) and for single drop ink impacts in this paper the above described hydrophobic and hydrophilic substrates can be considered to be non-absorbing.

Devices

Water droplets with radii in the millimeter range were created by pumping it through a needle using a syringe pump. The size of the droplets can be tuned by changing the diameter of the needle and the one that was used allowed to form drops of 2.4 mm. The velocity of the drops can be varied by almost one order of magnitude (0.3 to 3 m/s) by simply changing the height of fall (distance between needle and the substrate). The velocity was measured from the distance of travel between two images for which the acquisition times are well known.

Ink drops with a size of 65 to 74 μm were formed using an IJT 64 ID2 printhead.[8] Manipulation of the drive waveform allowed to form drops with velocities varying from 0.8 to 2.4 m/s. This is lower than the velocities which are usually used in ink-jet printing with the standard waveform. Droplets even more smaller, with a volume of about 70 picoliters, were created by sending 4 μs signals of 19V to an HP500 printhead. The velocity of the drops varied between 5 and 12 m/s depending on the ink composition.

The camera used to capture the impact and collision processes of large drops was a standard CCD camera with a LED illumination. For the small drops a PCO SensiCam fast shutter video capturing system was used. This is a high resolution 1280 x 1024 pixels, 12 bit cooled imaging camera which allows to take sharp snap shots of different experiments with a shutter time comprised between 500 ns and 2 μs. It was shown elsewhere[1] that the reproducibility from one experiment to the other is very good. Dual-exposure shot measurements are also possible with this camera and gives access to the velocity of the impacting drops. The illumination used for this camera is a cooled high intensity light source available from ILC Technology model R400-1 with front thermal glass. The cover glass prevents unwanted heating of the sample and also protects this very light sensitive camera.

For the large drop experiments a detector for sensing the falling drop was used and then the image was captured after a given delay time. Multiple shots taken at different times of multiple droplets were combined into one single "video" according to the pseudo-cinematography technique that has been described elsewhere.[8] The same technique is also used for the small drops with the added advantage that in this case the ejection time is perfectly well defined since the drops are formed with a printhead and there is no need to detect the falling drop in order to start the acquisition.

Finally once the grabbing process is terminated, a commercially available image processing software (Image Pro-Expert) is used to measure the transient diameter and height of the spreading drop from a gray scale image. Then the data are exported to spreadsheets and databases for further analysis.

Results and Discussion

To fulfill the objectives listed in the introduction part, experiments were performed with both large and small drops impacting either onto a solid substrate or colliding one onto another. In both cases, the measurements of the final and transient spreading diameter and height were taken for impact Weber and Reynolds numbers covering an order of magnitude of two and three respectively.

Impact of a Single Drop

Figures 2 and 3 show the evolution of large (2.4 mm) and of small (65 μm) drops impacting respectively at a speed of 1 m/s and 0.8 m/s. The numbers which are inserted on the figures give the time after impact in ms for large drops (figure 2) and in μs for small drops (figure 3). Because of the very small value of the Weber number, very close to 1, for the experiments performed with the microdrops, the spreadfactor is limited to less than 1.2 whilst for the large drops it attains almost 2.5 in accordance with previous results[1,4]. The evolution of the large drops impacting on a hydrophobic substrate are illustrated. When the drop touches the substrate, there is only a contact point so the diameter can be considered to be very small whilst the initial height is equal to the diameter. The characteristic time for the process can be taken as D_o/U_o where D_o is the diameter and U_o the velocity of the impinging drop which in this case is equal to 1 m/s. As expected, the largest diameter extending from around 3 ms to almost 7 ms, (1 to 3 times the characteristic time), corresponds with the lowest value for the height.

In figure 3 below, the snap shots taken at very short intervals of time are shown for the experiments performed with the IJT printhead using the SensiCam camera which has extremely short shutter times (every 10 μs for the first 4 pictures). This allows to show that the drop once again takes different shapes which are similar in nature to that given above in figure 2 for the big drop.

Comparing figures 2 and 3 one can note that the transient variations in diameter for the latter case are more limited because of the small values of the flow governing parameters namely the Reynolds and the Weber numbers.

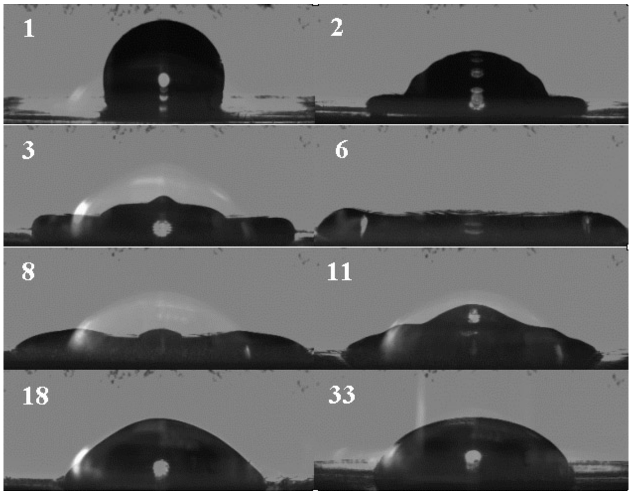

Figure 2. Experimental results of the impact phase of large drops recorded with a standard CCD camera

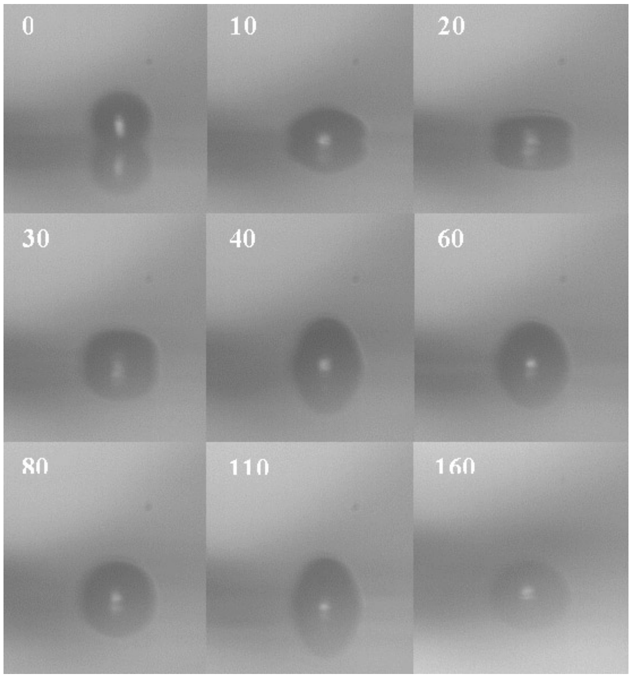

Figure 3. Impact and spreading of small drops

Besides the maximum value of the spreading which can be obtained through energy considerations[1,4], it is useful to have a simple model representing the drop impact transients. Indeed, the oscillation of the droplet consists of the inertial spreading of the droplet until it reaches its maximum diameter and subsequent oscillatory motions of recoiling and weak re-spreading.

The approach taken here to model the dynamics of single drop impact is to utilize the variational principle rather than the full Navier-Stokes equations which can be solved by different techniques.[10,11] This method is an approximate solution of the problem in which one has to assume a specified geometry (truncated sphere in this case) for performing the calculations. This geometry presents the advantage of relating simply the height and the diameter.

Adopting the procedure given in Bechtel et al.[12] and taking the viscous dissipation as proposed by Kim and Chun,[5] a differential equation is derived for determining the drop height as a function of time during contact.

$$A(h)h''-B(h)h'^2+C(h)h'+D(h) = 0 \qquad (1)$$

where h is the dimensionless drop height, the primes and double primes indicate first and second derivatives of height with respect to time and the other coefficients are some polynomial coefficients depending on the characteristics of the fluid and of the substrate.

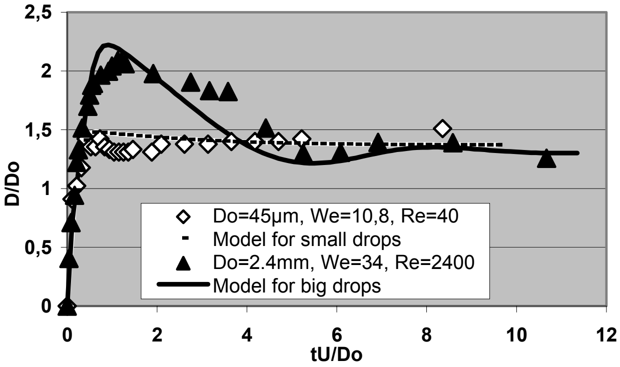

Figure 4. Comparisons between experiments and simulations using the variational model

In figure 4, the dimensionless diameter (D/D_o) is plotted versus dimensionless time (tU/D_o) for two sets of experiments performed with large drops and much smaller ones jetted by the IJT printhead. The viscous dissipation function is optimized so as to have agreement between the peak of the model and the actual data through the model for the maximum spreadfactor reported elsewhere[1]. All other computations are performed without further adjustments. The comparison between simulation and experiment is quite good knowing that the wetting angle and velocity profiles for example are hard to measure accurately. Moreover this model is able to reflect quite well the observed oscillations for the large drop which takes some time to get adjusted to the hydrophobic substrate i.e. before the drop acquires the equilibrium contact angle. To summarize it can be said that irrespective of the nature of the receiving substrate, the transient behavior can be predicted to some degree based upon the speed, size and fluid characteristics of the impinging droplet and the wetting properties of the substrate and this with a rather simple model.

Collision and Coalescence

Although there is a lot of literature[13,14] on the impact of a single drop onto a liquid film of uniform thickness, very few papers are really concerned with the collision process and coalescence of two drops.[6,7] The paper by Oliver[6] is just summarizing the main observations without too many explanations on the hydrodynamic behavior during collision and coalescence. Therefore new sets of experiments were performed with the following procedure. The first drop impinges onto the solid and reaches steady state, after some time, the second incoming drop impacts the first in a manner as close as possible to an axisymmetric landing because it is quite difficult to perform it correctly at least for large drops which are formed at the tip of a syringe.

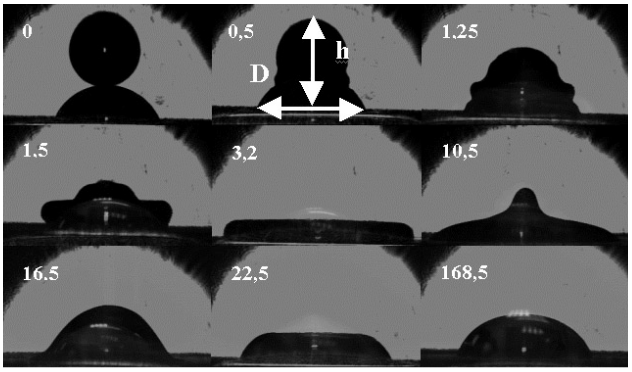

Figure 5. Experiments of multiple drop collision of big drops

In figure 5, the multiple drop collision tests conducted with a drop size of 2.4 mm and at a velocity at 1 m/s are shown. This is exactly the same operating conditions as for a single drop impacting on a dry substrate and the experiments have been done for the sake of easy comparisons with the previous case. The observations are performed with a standard CCD camera illuminated with a LED and a selected set of snapshots giving the multi-drop behavior as shown above. The inserts on the photographs show the time in ms and also give the definitions of liquid diameter (D) and height (h).

One can notice that the contact line is at rest until almost 1.5 ms with only swellings observed on the static drop at different locations and at different times. It can be suggested that this is due to the penetration of the incoming drop and that the flow really occurs when this drop hits the solid substrate. This assumption was further tested by performing experiments with micro-drops ejected by the IJT printhead at a velocity of about 2.4 m/s and the results are given in figure 6. In this case, the snap shots are taken every 5 μs in the initial stages with the SensiCam camera. Later the delay is adjusted accordingly.

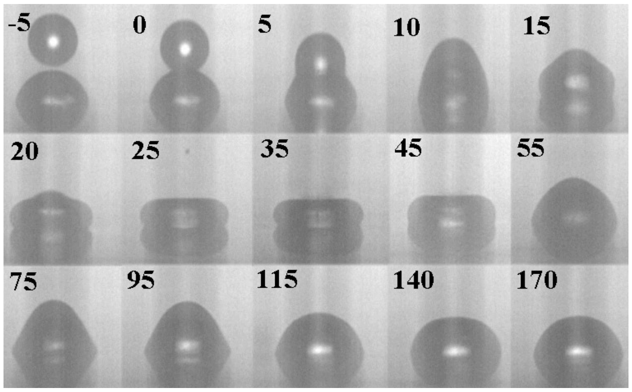

Figure 6. Collision behavior of small drops

Again in this figure, it can be noted that there is no evolution of the contact line up to a time of about 10 µs, corresponding to the penetration time of the second drop into the first one, and then after this latency time, the flow takes place with essentially observable oscillations on the height and almost no extension of the base diameter. This is probably due to the higher viscosity of this fluid compared to that of water.

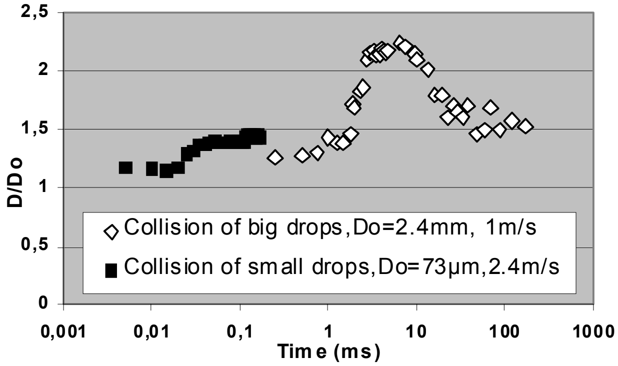

Figure 7. Transient evolution of the diameter for the multi-drop impacts

The observations of the snap shots of figures 4 and 5 are exemplified in figure 6 for what concerns at least the variations of the diameter of the drop versus time. The diameter is rendered dimensionless by dividing by the diameter of the impacting drop as for the single drop case. As said previously there is a latency time with no variation of the base diameter which can be attributed to the transit time of the incoming drop. This is followed by an increase of the diameter which may be more or less important depending on a large number of parameters which may be for example the kinetic energy of the incoming drop, the energy lost by friction, the surface energy of the merged drops and so on.

It is observable for both large and small drops (figures 4 and 5) that at long times - of the order of 170 ms for the large drops and 170 µs for the small drops - one obtains a single mass of fluid with a shape (equilibrium contact angle) very similar to the case of a single drop. It may be useful to find out whether the variational method is appropriate for representing the oscillations of the merged mass of fluid corresponding to the volume of two drops of same initial size.

The results are given in figure 8 where the transient dimensionless height is shown as a function of a dimensionless capillary time. The blank lozenges correspond to the big drops whilst the filled squares represent the small drops. Also on the same figure are the simulations for a merged drop (continuous and dashed lines for small and large drops respectively).

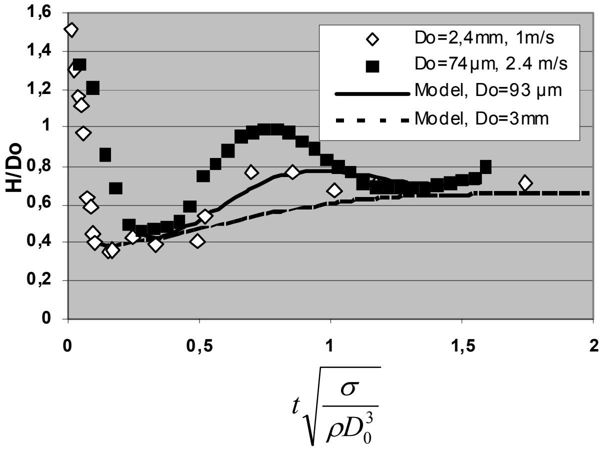

Figure 8. Transient oscillations of the merged mass of fluid

It can be noted that there is a much better agreement in terms of amplitude of oscillation for the small drops. This is evident from figures 5 and 6 showing that the collision behavior of small drops can be quite well represented by a truncated sphere at all times of the process. This is indeed the geometry that was assumed for performing the calculations.

The theoretical frequency of oscillations is given by the quantity

$$\sqrt{\frac{\sigma}{\rho D_0^3}}.$$

The comparisons with the experimental results show that the percentage of error is comprised between 15 and 20% which tends to show that indeed once the spreading process is terminated, the two drops are completely merged and form a single mass of fluid. This should help to render somewhat more simpler the calculations for the collision and coalescence process.

Conclusions

In this paper, the collision dynamics of single and multiple droplets impinging on a variety of surfaces have been studied both experimentally and from a modeling point of view. The measurements performed first on the impact of single large and small drops help to resolve the different regimes of spreading. These measurement also show the relevance of the dimensionless numbers for describing accurately the flow and this is confirmed by the simulations using the variational model giving the transient diameters and heights during the impact process. In the second part of the paper, for the first time in the literature, low velocity axisymmetric drop onto drop collisions, similar to that encountered in actual matrix ink-jet printing are reported. The measurements show that the incoming drop is first absorbed into the static drop before any significant variation of the contact line takes place. The impact of the incoming drop onto the solid substrate leads to the spreading and oscillations of the whole mass of fluid, fairly well rendered by model predictions, and this seems to be critical in defining the overall image quality on substrates.

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Acknowledgments

The authors are indebted to the Belgian and French governments (IWT, MNRT) for partial financial support of this work through projects PROFIJET and Σ ! 2911 PRODIJ. The Agfa Ink Jet team is thanked for their help in developing the inks and media used throughout this study.

Biography

Guido Desie got a Ph.D. at the K.U.Leuven, in the field of physicochemical analysis of enzymatic systems. In 1987, he joined Agfa Gevaert, Belgium, where he was involved in R&D of physical properties of film materials. From 1991, he was involved in R&D of Ink Jet and Toner based digital printing techniques. He is the co-author of about forty granted patent families mainly in the fields of Ink Jet and Toner Jet printing.